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Room-temperature operation of GaInAs/InP based ballistic rectifiers at frequencies up to 50 GHz

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Abstract. Ballistic rectifiers are realized in high-mobility GaInAs/InP quantum well materials using electron beam lithography and wet chemical etching. The devices are made small enough to function even at room temperature. Furthermore, we demonstrate that the devices operate at frequencies at least up to 50 GHz.

Introduction

Recently, a novel semiconductor ballistic rectifier fabricated from a GaAs/AlGaAs heterostructure was demonstrated [1]. In contrast to conventional semiconductor rectifiers, such as diodes, the ballistic rectifier consists of neither a p-n junction nor a barrier structure. The idea behind this ballistic rectifier is the guidance of electrons by a symmetry-breaking scatterer in the ballistic electron transport regime, where electrons are only scattered from designed geometrical boundaries and not from defects. This new working principle allows for very high working speed and also does not give any voltage or current threshold. Recently, it has been shown that the ballistic rectifiers can be realized in high-mobility GaInAs/InP quantum well materials [2], which gives higher efficiency and higher operation temperature of the devices. In this work, we demonstrate that the devices not only function at room temperature, but also operate up to at least 50 GHz.

1. Fabrication

The material used in this work is a modulation-doped $Ga_{0.25}In_{0.75}As$/InP heterostructure (details in ref. [3]) in which electrons are confined into a two-dimensional electron gas (2DEG) in a 9 nm thick quantum well, located 40 nm below the surface. The GaInAs/InP system is used because it has been proved to have less surface damage after etching, and therefore weaker electrical depletion around structures and higher room-temperature electron mobility than a GaAs/AlGaAs heterostructure. The 2DEG has the following parameters extracted from the Hall measurements at room temperature: carrier density 4.5×10^{11} cm^{-2} and mobility 12000 cm^2/Vs. Thus, the elastic mean-free-path of the electrons is 130 nm at room temperature. Using electron beam lithography and wet chemical etching (details in ref. [4]), a triangular area is etched away in a cross junction on conventional Hall-bars and also on specially designed layouts for high-frequency measurements. The scanning electron micrograph of the central part of the device is shown in Fig. 1. The antidot has an upper sidelength of 250 nm and height 230 nm. The lithographical width of the source (S) and drain (D) channels is 100 nm, and the upper (U) and lower (L) channels 500 nm.

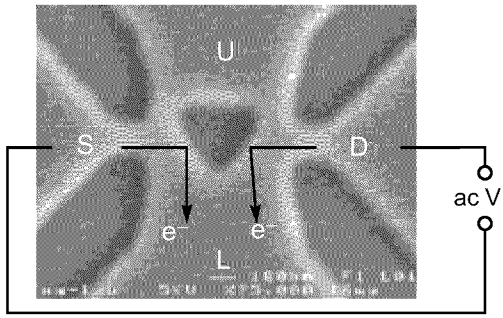

Fig. 1. Scanning electron micrograph of the middle part of the device. The etched triangular antidot scatters most of the electrons out of S and D downwards, independent of the direction of the applied SD voltage, as illustrated by the arrows

2. Results and discussion

Since the elastic mean-free-path of the electrons in our sample is comparable to the size of the central part of the device at room temperature, we expect that the electron transport will be, at least partially, ballistic in the device. Thus, the electron scattering from the triangular boundaries, as shown by the physical picture in Fig. 1, will largely determine the transport properties. If a finite voltage is applied to S and D, the applied field will enhance the electron transmission along the arrows shown in Fig.1 while the electron transmission along the reverse direction is less affected. This results in an accumulation of electrons in the L channel and therefore a negative potential at L. Indeed, our devices show this behavior. The average (dc) voltage between L and U as a function of applied (ac) SD voltage is measured at different temperatures, and the result is presented in the inset of Fig. 2. Smaller output at higher temperatures is expected since the elastic mean-free-path decreases when the temperature increases. Even there is no pronounced output from the device at low SD voltages at room temperature in inset of Fig. 2, the main curve in Fig. 2 plotted in a large SD voltage range shows that the device indeed works at room temperature. This proves that the transport of at least some electrons is still ballistic in the device. The quadratic dependency of the LU voltage, shown by the quadratic fit (solid line) on the SD voltage is expected from ref. [5].

The parasitic capacitance between electrical contacts is very low for this type of devices (the contacts are located on the sides instead of the surface and substrate, as for vertical devices). Also the working principle of this device does not rely on any minority carrier diffusion and no barrier structure is used along the current direction at all. Therefore we can expect that the ballistic rectifier should function at very high frequencies. Room-temperature operation of the ballistic rectifiers makes it much easier to perform high-frequency experiments than measurements in a cryostat. Figure 3 shows the average device output (measured by a DC multimeter) versus the power of the high-frequency SD signal (reading from the signal source) of another device at room temperature. The frequency of the SD signal is fixed at 50 GHz. As we can see, the output of the device is approximately linearly dependent on the 50 GHz signal power, which agrees with the quadratic dependency on applied voltage shown in Fig. 2. Also, we should point out that due to impedance mismatch between the signal source and the device, only a small fraction of the power from the signal source is actually absorbed by the device at 50 GHz. Therefore, the real sensitivity of the device is higher than that shown in Fig. 3. Although it is not possible for us to test the devices at frequencies higher than 50 GHz, from the working principle we

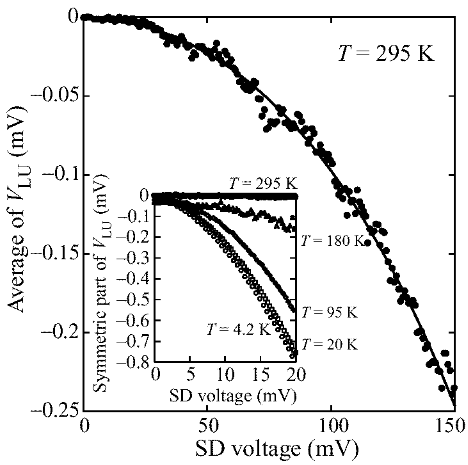

Fig. 2. DC output as a function of SD voltage at room temperature: dots are experimental data and solid line is a quadratic fit. The inset shows the result at lower temperatures.

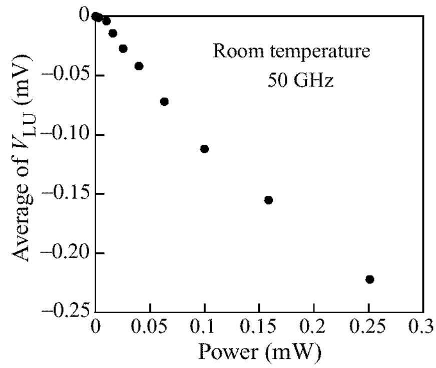

Fig. 3. DC output versus the power of the 50 GHz signal, which is applied to the devices via coplanar probes.

can expect them to work at much higher frequencies, possibly up to THz regime.

3. Conclusions

In this work we have shown that the ballistic rectification effect can be realized at room temperature in high-mobility InGaAs/InP quantum well materials. This is one of the very few types of electronic nano-devices which have been shown to have room-temperature operations so far. We have also demonstrated operations of the ballistic rectifiers at 50 GHz, which makes them very promising for practical applications.

Acknowledgements

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